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Process heat generation with parabolic trough collectors for a vegetables preservation industry in Southern Spain

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Abstract

In the present work the use of a parabolic trough solar plant to generate process heat steam for a food processing application is studied. The food processing industry, devoted to vegetables preservation by thermal treatment and canning, is located in the Southern Spain region and demands saturated steam at 7 bar with an total annual consumption of 148MWh. The base solar plant configuration analyzed consists on a parabolic trough solar field, thermally stratified energy storage, and a steam generator (unfired boiler). The influence of the main operational variables of the solar plant are studied, namely the solar field outlet temperature and the steam generator return temperature to assess its influence in the main energy based design indicators of the plant. Furthermore the possibility of including a pre-heating heat exchanger before the steam generator is also evaluated. The obtained results of this study show the suitability of changing the present energy input scheme of this industry.

Keywords: Process Heat; Food Processing; Parabolic Trough; Saturated Steam

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Nomenclature

A	solar field aperture area, m^2
A_{hx}	heat exchanger area, m^2
b_{1L}	first coefficient of incidence angle modifier, 1/degree
b_{2L}	second coefficient of incidence angle modifier, 1/degree^2
c_1	first order heat loss coefficient of the solar collector, W/(m^2 K)
c_2	second order heat loss coefficient of the solar collector, W/(m^2 K^2)
DNI	direct normal irradiance, W/m^2
F_s	solar fraction, [-]
HX	heat exchanger
$K_{\theta b}$	incidence angle modifier for solar direct radiation, [-]
$K_{\theta L}$; $K_{\theta T}$	longitudinal and transversal incidence angle modifier, [-]
Q_{aux}	auxiliary energy, kWh
Q_{solar}	solar energy, kWh
T_{ret}	steam generator return temperature, ºC
T_{set}	solar field set point temperature, ºC
V	storage volume, m^3
$\eta_{0, DNI}$	optical efficiency, [-]
η_{plant}	solar plant efficiency, [-]
θ_L; θ_T	longitudinal and transversal incidence angle, degree

1. Introduction

The food sector represents an important fraction of the total industry energy demand in Spain with a total aggregated consumption of 30166GWh, of which 98% are situated in the low-medium temperature range [1]. From this consumption approximately 20% comes from the region of Andalucía located in Southern Spain. Low-pressure saturated steam is a common heat distribution medium used by the food sector industries, however its production requires higher temperatures in the solar plant. The Andalucía region benefits from favorable weather conditions with DNI levels above 1700kWh/(m^2year) allowing the use of concentrating solar technology which can reach high temperature levels with the necessary efficiency. This fact allows this class of plants to be integrated directly to the central steam distribution network at the supply level, taking advantage of the existing distribution network and thus simplifying the integration process. Moreover, by addressing the total heat demand the solar plant can be designed to cover higher solar fractions. A food processing preserved vegetables industry is studied and its heat consumption is evaluated in an hourly time basis. The industry is located in a rural area in the province of Almería and dedicates to glass canning of tomatoes and other vegetables. Dynamic simulations are carried out to study the influence of the solar field distribution, orientation and thermal storage size on the performance of the total system.

2. Production and processes

The preserved vegetables industrial plant is situated in a rural zone and has a total annual production of 91t. The production consists on preserved vegetables (mainly tomato) being the main types of products produced jams, tomato sauces (fried tomato, sofrito), natural tomatoes (grated tomato, gazpacho) and roasted pepper. The products are blanched to eliminate its skin, and afterward cooked, packed and sterilized. Some products do not require blanching (they are cooked and processed with the skin) and others do not require cooking. The factory produces a different product each day and works with a single day shift with stops at weekends. The total process heat annual consumption is 148MWh which are supplied by a fuel oil steam boiler that generates saturated steam at 7bar. From this energy production approximately 64% are consumed by the processes, and the remaining 36% are thermal losses in the distribution (Fig.1), boiler efficiency, condensate return and steam flash. The factory is located in a rural area with no adjacent buildings.

The energy demand profile is evaluated in an hourly time basis and varies for each month of the year in function of the products processed and labor days. Fig. 2 shows the demand evolution and working days. Furthermore, in this study a preliminary energy consumption analysis identified potential energy efficiency measures that can improve the performance of the industrial plant and thus are expected to increase the overall efficiency of the combined system of solar plant plus industrial process.

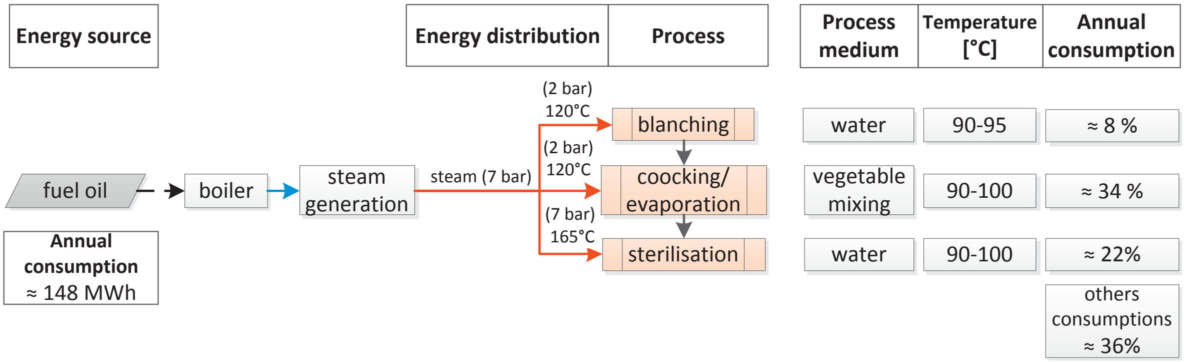

Fig. 1. Industrial process diagram.

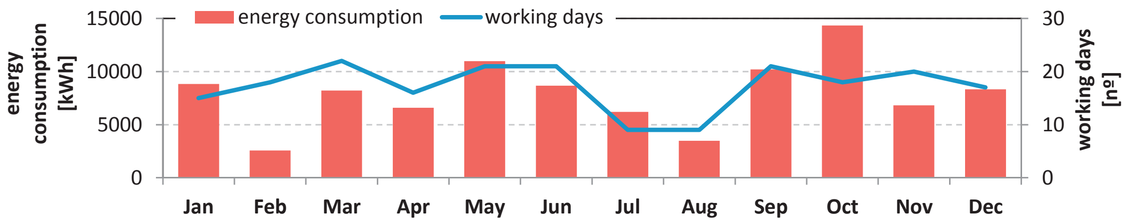

Fig. 2. Monthly process energy consumption and number of working days.

3. Solar plant

The collector considered for the solar field is a small-sized parabolic trough [2], and the two main orientations (N-S, E-W) are studied. Demand occurs mostly during the daytime, however, there are production stops at weekends so a configuration with storage is studied. The heat transfer fluid selected is Therminol 55 and a steam generator is used to couple the solar plant with the industrial process (Fig. 3).

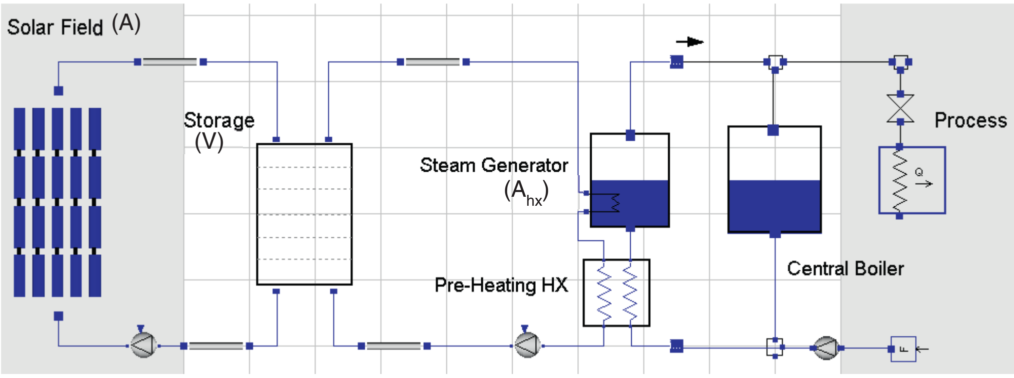

Fig. 3. Diagram of the parabolic trough solar plant and industrial process.

A pre-heating heat exchanger is included before the steam generator to lower the solar field inlet temperature and increase its efficiency. A configuration with integration on supply level was selected due to the favourable available direct radiation conditions available in this location, to allow addressing a combined profile that is more adequate to the solar energy generation, and also to benefit from the existing distribution network [3].

The solar field model consists in a distributed dynamic set of longitudinal segments with mass, energy and momentum balances which are coupled with a heat loss equation derived from empirical characterization curves [4, 5].

The Table 1 shows the data of the solar collector selected, where the collector parameters bellow are based on direct solar irradiance and derived from the collector parameters determined from characterization tests in quasi-dynamic conditions [2, 6].

Table 1. Performance and incidence angle modifiers for the parabolic trough collector.

Performance	**Incident angle modifiers ($K_{\theta b}$) (Ec. 1)**
$\eta_{0,\,DNI}$ [-]= 0.689	b_{1L} [1/degree]= -0,0003672
c_1 [W/(m^2 K)]= 0.36	b_{2L} [(1/degree)^2]= -0,0000106
c_2 [W/(m^2 K^2)]= 0.0011	

$$K_{\theta b}(\theta) = K_{\theta L}(\theta_L)\, K_{\theta T}(\theta_T) = \left(1 + \frac{\left(b_{1L}\,\theta_L - b_{2L}\,\theta_L^{\,2}\right)}{\cos\theta_L}\right) 1 \tag{1}$$

Where, $K_{\theta L}$ [-] and $K_{\theta T}$ =1 [-] are the direct modifiers of incident angle and θ_L [degree] and θ_T [degree] the longitudinal and transversal incident angle. The vertically stratified tank model is constituted by a set of lumped energy and mass balances, coupled with a heat loss coefficient. The steam generator is consisted by a set of longitudinally transient energy balances between the sensible side (thermal oil) and the latent side (saturated liquid and steam). The fuel oil central boiler is modeled to provide the necessary auxiliary heat demand, while maintaining the pressure in the main steam line.

The model was implemented in the open-source object oriented high-level modelling language Modelica.

Due the fact that this particular location benefits from high values of direct irradiance the integration at the central level where temperatures are higher is possible. This allows us taking advantage of the existing heat distribution network and addressing the combined demand of the various individual processes.

The direct integration to a single process would lower the temperature, however the demand profile would have even longer and more frequent idle times with no consumption, hence seriously increasing the energy wasted and thus lowering the performance of the solar plant. By combining all the processes the demand adjusts better to the solar resource. For this particular thermal application demand profile the solar field orientation selected was North-South to maximize the collection of solar radiation during all year. The number of collectors in series was selected accordingly with the temperature differential required, taking in consideration that there is a minimum mass flow rate conditions for the solar collector due to the necessity of reaching sufficiently high turbulence levels to evenly cool the absorber tube. The number of collectors in parallel was selected based on the power output intended. A requirement of a minimum annual solar fraction contribution to the industrial application was considered as design criteria, which is furthermore balanced with a judicious power demand selection based on a sensitivity analysis to avoid prohibitive thermal energy losses and low overall thermal efficiency. The thermal energy storage design was based on guidelines for industrial process heat applications considering a fluctuating daytime consumption demand [7].

4. Results

Simulations were conducted to evaluate the contribution of the solar plant to the energy demand of the industrial process for a reference design. The figure below shows the results obtained by simulation of the monthly solar fraction, the solar plant efficiency, thermal demand, solar power delivered and auxiliary power during the year, for the reference conditions studied.

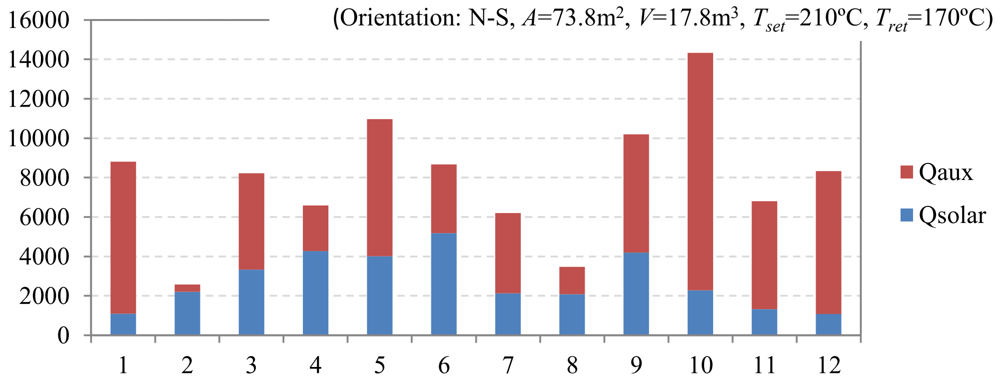

Fig. 4. Monthly auxiliary and solar energy input [kWh].

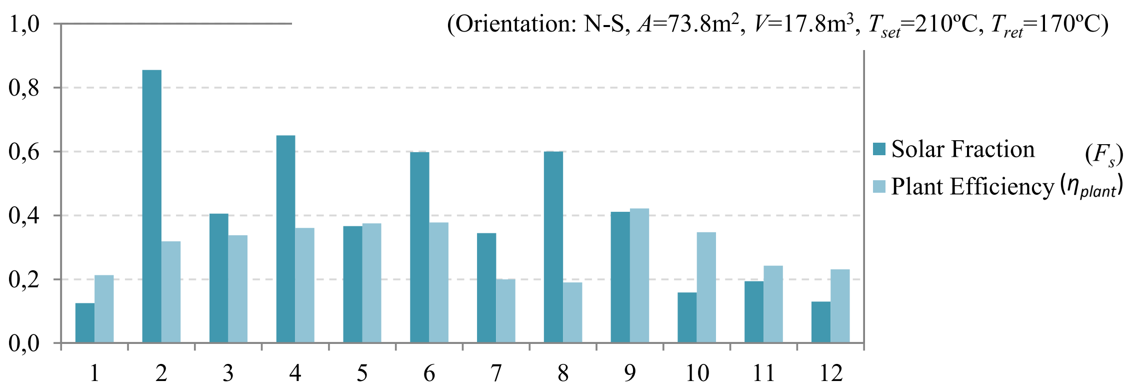

Fig. 5. Monthly average solar fraction and efficiency.

During the summer months the solar gain is low because the thermal demand in that period is characterized by sporadic peaks of very high intensity, separated by large periods of no thermal demand between them. The dynamics of this particular thermal demand is very hard to address for a solar thermal system, and furthermore, the contribution of these particular months to the yearly energy demand is small, so it may be hard to justify solutions as increasing the solar field or storage size, from a strictly economic point-of-view.

It can be observed that in months where there is few energy demand but the solar resource is high such as summer months the solar plant efficiency is very low (below 20%) due to the excess energy that is wasted.

Also during the winter months it can be seen that the solar energy contribution is very reduced (below 20% in most cases) due to the lack of solar irradiation during those months and also due to the relatively high demand during most of them. The average annual solar fraction obtained is 34.9% and the annual overall efficiency is 30.4%.

Table 2. Influence of the orientation of the solar field.

Orientation	F_s [-]	η_{plant} [-]
North-South	34.9	30.4
East-West	33.4	31.1

It can be verified that the North-South orientation produces the highest solar energy contribution (Table 2), due to the fact that it is able to collect more energy in an annual basis. The influence of the set point temperatures (T_{set}) (outlet of the solar field and return of the steam generator) were also studied. Table 3 shows the results obtained:

Table 3. Influence of the integration temperatures in main design figures.

T_{ret} [ºC]	T_{set} [ºC]	F_s [-]	η_{plant} [-]	A_{hx}[m^2]
170	190	30.0	26.0	8.0
	210	34.9	30.4	5.5
	230	37.1	32.3	4.3
180	190	28.9	25.2	5.1
170		30.0	26.0	8.0

Regarding the effect of the set point temperature, it can be observed that increasing the temperature allows to increase the energetic performance of the plant and at the same time reduce the size of the unfired boiler heat exchanger. This is due to the fact that by increasing the temperature differential between the return and the outlet of the storage tank we can increase its energy density per unit of area of the solar collector field without increasing the external area of the tank (because the geometry remains the same). Therefore this allows us to cover more periods of no consumption without the need to increasing the storage size, cost and external area exposed per unit area of the solar field. The limit to this benefit can be set by one of the following two elements: the first is the maximum temperature allowed by the specific collector manufacturer in the solar field outlet. In this case the highest value simulated is considerably close to that value. The other limitation is the maximum temperature allowed by the storage tank, which also depends on the specific manufacturer. If the efficiency curve of the collector also has a significantly decrease at high temperatures, the reduction in efficiency can overcome the gain due to increase of energy density in the storage tank and lead to a lower ideal temperature.

It can be also be seen that by lowering the return temperature (T_{ret}) the efficiency of the solar plant increases since the average temperature in the solar field decreases and thus the thermal losses are reduced. However to lower the return temperature it is necessary to use larger heat exchangers which can be more expensive. From an energetic point a view this trade-off is not visible and hence the larger the heat-exchanger the better, although above a certain value the effect is almost unnoticeable since the outlet temperature of the steam generator heat exchanger is limited by the cold side (the saturation fluid) in the unfired boiler.

Further increasing the temperature differential between the set point and the return temperature of the steam generator is possible with an extra pre-heating heat exchanger. Simulations reveled that it allows a small reduction in the return temperature of the solar steam generator. This reduction is small compared with the temperature differential in the latent stage of the steam heat exchanger since sensible heat is typically small in comparison with latent heat. Hence although this option increases the solar field thermal efficiency and the thermal energy storage energy density, these benefits come at the cost of an extra element and thus can only be evaluated from an economic optimization point of view.

5. Conclusions

The possibility of production of saturated steam with a parabolic trough solar plant for a food processing industry with an unfired boiler configuration was studied.

The first conclusion is that a significant part of the demand can be covered with a small solar field, thus posing no problems in available area, and easily reaching reasonable annual solar fractions since the demand is relatively low. However this solar fraction comes at the cost of a low-medium solar plant annual thermal efficiency since there is a significant degree of thermal energy that cannot be used during the idle periods such as the summer, where there is the largest potential to generate solar energy. Furthermore the necessity to storage during prolonged periods at this temperature range can lead to significant thermal losses in the storage tank if it is not properly insulated. It was concluded that for this class of demands that are characterized by high volatility, long periods in idle mode, and high temperature requirements, a configuration with thermal energy storage is mandatory if significant higher solar fractions are required. It becomes clear that one of the key factors for deploying such solar plants is the development of very efficient and cost effective thermal energy storage for this relatively high range of temperatures. These results also support the recent motivation to the continuous R&D efforts being made by several institutes to tackle this particular challenge. The analysis made also showed that the use of a heat exchanger allowed increasing the thermal efficiency of the solar field by lowering its inlet temperature, and at the same time increasing the energy storage density, thus reducing its specific losses, however these benefits come at the cost of an extra element to the system and thus are recommended to be evaluated from an economic point of view.

Acknowledgements

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